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LABORATORY EVALUATION OF RECYCLED HOT MIXES

(VOLUME 1)

LOW TEMPERATURE PERFORMANCE

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LABORATORY EVALUATION OF RECYCLED HOT MIXES

(VOLUME 1)

LOW TEMPERATURE PERFORMANCE

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ABSTRACT

As part of a long term monitoring program of recycled hot mixes (RHM), the Ministry of Transportation, Ontario has acquired limited performance data from 7 test sites to evaluate the performance of recycled hot mix asphalt pavements. The initial evidence indicates that RHM mix design needs improvement particularly with respect to cracking. As a result, a project was undertaken to evaluate the potential of recycled hot mixes to resist cracking. This report presents the results of such evaluation with respect to low temperature cracking.

The resistance to low temperature cracking has been investigated in terms of both limiting stiffness and fracture temperature criteria. In the limiting stiffness approach, McLeod's tentative design guide was used to evaluate the resistance of the mixes to thermal cracking. In the case of fracture temperature criterion, the failure strains under uniaxial direct tension tests and the induced thermal strains were compared to estimate the fracture temperature of asphalt mixes. The test results based on both criteria confirmed the common belief that the recycled hot mixes are more susceptible to thermal cracking than the conventional/virgin hot mixes. Additionally when the findings of results based on both criteria were compared with the observed field data, it appears that the fracture temperature criterion is more suitable than the stiffness criterion.

ABRÉGÉ

Dans le cadre d'un programme de contrôle à long terme des mélanges préparés à chaud recyclés, le ministère des Transports de l'Ontario a recueilli des données partielles sur les performances, provenant de 7 sites d'essai, et ayant pour objectif l'évaluation des performances des revêtements d'asphalte recyclé préparés à chaud. Les résultats initiaux indiquaient que les mélanges recyclés préparés à chaud nécessitent des améliorations, surtout au niveau de la résistance à la fissuration. Un projet a donc été mis sur pied dans le but d'évaluer la capacité des mélanges recyclés préparés à chaud de résister à la fissuration. Ce rapport présente les résultats de cette évaluation pour ce qui est de la fissuration à basses températures.

La résistance à la fissuration à basses températures a été examinée des points de vue de la rigidité limite et de la température de rupture. Pour ce qui est de la rigidité limite, on s'est servi du guide de conception provisoire McLeod pour évaluer la résistance des mélanges à la fissuration thermique. Quant à la température de rupture, on a comparé les déformations sous essai de tension directe uniaxiale et les déformations thermiques induites, pour évaluer la température de rupture des mélanges d'asphalte. Les résultats des essais basés sur les deux critères ont confirmé le fait que les mélanges recyclés préparés à chaud sont plus sensibles à la fissuration thermique que les mélanges préparés à chaud conventionnels. De plus, en comparant les résultats des deux critères avec ceux obtenus sur le terrain, on constate que le critère de température de fissuration est mieux adapté que celui de rigidité.

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1 BACKGROUND

In early seventies, the rising prices of asphalt binders contributed significantly to promote recycling of pavement materials as a cost saving alternative to the traditional resurfacing of highway pavements. Based on the initial evidence of promising benefits, a number of agencies had sponsored research [1-9] to investigate into the merits of reclaiming and recycling pavement materials. As a result, in 1978, the then Ministry of Transportation and Communications, Ontario, set up a task force to study the feasibility of using hot mixed recycled asphaltic concrete for highway pavements.

After intensive investigation, the task force presented a report to senior management recommending the use of hot mixed recycling as a viable alternative for all rehabilitation projects. Based on their recommendations the management decided to generate a large hot mixed recycling program at the earliest opportunity [10]. In 1980, the Ministry of Transportation, Ontario, embarked upon over 490,000 tonnes of hot mixed recycling which represented about 19% of 2.6 million tonne annual paving program. Since then, 3.5 million tonnes of recycled hot mix pavement have been laid in the Ontario provincial highways with an average of 700,000 tonnes per year or 45% of the Ministry's annual hot mix placement [11].

2 PROBLEM STATEMENT

Following the construction of about 80 recycled hot mix (RHM) projects in Ontario, the Ministry of Transportation has initiated a long term monitoring program to evaluate the performance of RHM asphalt pavements on a yearly basis. Consequently, 7 test sites (Table 1) from different contracts covering all the regions of Ontario were selected. Initial evidence, based on the limited

performance data taken from these sites after 4 to 5 years of construction, suggests that RHM mix design needs improvement particularly with respect to cracking. This created a need for an objective performance evaluation of RHM as compared to the traditional HL4 mix. With this need in mind, an experimental program has been undertaken to carry out a series of laboratory tests to evaluate the low temperature performance of recycled asphaltic concrete mixtures.

3 SCOPE AND OBJECTIVES

The basic scope of the study is to investigate the relative resistance of recycled hot mixes to thermal cracking as compared to conventional/virgin hot mix. In more specific terms, the objective of this study can be stated as follows:

1) To summarize the existing method of approach and select the appropriate criteria for evaluating the low temperature susceptibility of recycled hot mixes,
2) To design an experimental program to determine the criteria selected in step 1,
3) To analyse the test results and compare the low temperature performance of various recycled and conventional hot mixes,
4) To identify the best criterion for a future low temperature evaluation study, and
5) To suggest improvement, if any, for future mix design procedures.

4 METHOD OF EVALUATION

A number of procedures have been developed for evaluating low temperature susceptibility of bituminous materials and they can be categorized as follows:

1) use of asphalt specifications,

2) use of limiting stiffness,

3) predicting fracture temperatu , and

4) estimating cracking frequency.

Use of asphalt specifications is not applicable to this case because it deals with only the binder and not the overall performance of asphaltic concrete. The approach of using limiting stiffness has evolved as a result of field and test section observations, as well as much of the laboratory work [12]. The method involves the determination of mix stiffness and compares such values with an established design guide [13]. If the estimated value exceeds the design value, cracking is likely to occur.

The prediction of fracture temperature is based on the thermally induced stresses or strains in the bituminous layer. When the induced stress or strain due to temperature drop exceeds the failure stress or strain, cracking is expected to occur and the corresponding temperature is called the fracture temperature. The higher the fracture temperature of a material, the lower is its resistance to thermal cracking. In a design situation, if the estimated fracture temperature is less than the winter design temperature [14], cracking is expected to occur and the design should be rejected or modified.

The approach of estimating cracking frequency was developed at the University of Waterloo [14]. It is based on extensive background work in developing apparatus and methods for characterizing the low temperature response of bituminous materials, and on relating the results of laboratory investigation to field observations. This approach requires stiffness of asphalt cement and not asphaltic concrete. As such this method is not considered in this investigation.

In summary, the method of evaluation is confined to two criteria: limiting stiffness and fracture temperature. Both criteria are determined experimentally and they are described in the following sections.

5 EXPERIMENTAL PROGRAM

A laboratory experimental program was designed specifically to investigate the potential use of different asphaltic concrete mixes to resist thermal cracking using limiting stiffness and fracture temperature criteria. The program consists of a series of laboratory tests performed on a conventional HL4 mix and different recycled hot mix specimens in order to establish test data that can serve as performance indicators for the mixes. The type of tests included in the program are:

1) direct tension tests using servo hydraulic testing (MTS) equipment, and
2) thermal contraction tests.

A brief discussion on the sample preparation, material selection and individual testing procedure is presented in this report. However, a detailed information on theories, applications and interpretation of the results of these testings can be found in reference [15].

5.1 SAMPLE PREPARATION AND MATERIAL SELECTION

Test samples were prepared according to procedures given in ASTM D3202 (Beams). Materials for standard HL-4 mix were selected according to the mix design procedure of the Ministry of Transportation (16). For recycled hot mix specimens, two types of materials were used; one was plant mixed materials and the other was laboratory mixed materials. The former were obtained directly from batch or drum plants and the latter were prepared in the laboratory using aggregates, reclaimed asphalt pavement (RAP) materials and asphalt cement as supplied from the field. However, for contracts 81-74 and 82-04 the source of supply of binders for laboratory mixes was different from that for plant mixes because of non-availability of the binders as supplied from the field. For Contract 83-43 no lab specimen was prepared due to lack of RAP materials.

Mix design requirements for recycled hot mix are given in Table 1, and the traffic growth for each test section is given in Table 2. Numbers within parentheses of Table 1 are the plant check results of all the contracts under investigation.

Because of time constraints, the laboratory tests were limited to samples and materials obtained from five contracts only. The selected contracts were 81-224, 82-19, 83-43, 81-74 and 82-04 which represent different regions and cover a wide range of asphalt cement grades and RAP/virgin recycling ratios. The asphalt binder properties of the selected recycled hot mixes are given in Table 3. As well, the description of aggregates used for each contract is provided in Table 4.

The results of sieve analysis of aggregates used for these mixes are presented in Table 5.

5.2 DIRECT TENSION TEST

Direct tension tests were performed at 21°C, -5°C, and -35°C to determine the tensile strengths, strains, and stiffnesses of different mixes. Factorial arrangement for the testing program is shown in Table 6. The specimen was pulled at a constant rate of extension (3×10^{-2} mm/min at -5°C and -35°C, and 5mm/min at 21°C) until failure occurred. The stress, strain, and stiffness at failure were recorded and the plots of stress-strain graph were obtained. For testing at temperatures -5°C and -35°C, the specimens were pre-cooled overnight prior to testing. An environmental chamber was used to maintain the low test temperatures of -5°C and -35°C.

5.3 THERMAL CONTRACTION

Determination of thermal contraction is an integral part of the analysis of the thermal behaviour of asphalt mixes. Thermal contraction was used to estimate the induced strain due to thermal shrinkage under restraint condition. Beams of 101mm length having a cross-section of 76x76mm were used to determine the thermal contraction. Set points were selected on each sample and the length of the specimens were measured using digimatic caliper before and after cooling the specimens for 24 hours at each temperature. Readings were taken during both the cooling and heating cycle for comparison. Thermally induced strains at various temperatures are calculated for all mixes (Table 7 and 8) by dividing the actual contraction of each specimen by its original length.

6 ANALYSIS OF TEST RESULTS

As discussed previously in section 3, the low temperature cracking has been investigated in terms of both limiting mix stiffness and pavement fracture temperature criteria. The results of the investigation using these two approaches are presented as follows:

6.1 LIMITING MIX STIFFNESS CRITERION

In the limiting stiffness approach, McLeod's tentative design guide [14] has been used to investigate the resistance of each mix to cracking at low temperature. Figures 1-5 compare the stiffness-temperature variation of recycled hot mixes with that of the conventional mix together with McLeod's maximum and minimum stiffness criterion for various temperatures. Figures 6 and 7 give the stiffness distribution of various mixes at -35°C, -5°C, & 21°C. As well, the comparison of stiffness between plant and laboratory mixes are given in Figure 8. It appears from these figures that none of the mixes has resistance to cracking at very low temperature. However, it is useful to note at this point that McLeod's values for limiting stiffness according to Asphalt Institute Report [17] may be too conservative because of its dependency on asphalt PVN data which tend to give lower stiffnesses than the actual measured values. Therefore, more experimental data correlating the observed pavement cracking temperatures with the measured low temperature stiffnesses are required to establish a realistic value for limiting mix stiffness. Nevertheless, limiting stiffness concepts can be used to rank different mixes in order of their resistance to thermal cracking. The following section compares briefly the potential resistance of recycled plant and laboratory mixes with the standard HL-4 mix on the basis of stiffness criterion.

6.1.1 Laboratory Test Results

The test results for plant and laboratory specimens are compared with those of HL-4 specimen. The following observations are made from Figures 1 to 8:

1) The stiffness increases (Figures 1 to 5) with decrease in temperature for all the mixes. The increase is significant at temperatures below -5°C. The recycled hot mixes from all contracts exhibit higher stiffness values than the HL-4 mix at all temperatures indicating that they are more susceptible to thermal cracking than the HL-4 mix.

2) Among recycled hot mixes (Figure 8), laboratory mixed specimens exhibit higher stiffness values at 21°C (about 26% for 81-74; 54% for 81-224; 60% for 82-19, and 116% for 82-04) than the plant mix specimens and lower stiffness values at -35°C (about 38% for 81-224; 142% for 82-04; and 126% for 82-19) with the exception of the one from contract 81-74 whose stiffness value is about 43% higher than the plant mix. The reason for this exception is difficult to explain because of limited data. However, in general the differences between the results of plant and laboratory mixed specimens may be perhaps due to different temperature susceptibility property of asphalt cements as caused by various mixing and production procedures used for preparing plant and laboratory mixes. Temperature susceptibility of paving asphalt is referred to the change in consistency (penetration or viscosity) that an asphalt undergoes for a given change in temperature. According to McLeod [18], asphalt cements having the same penetration at 25°C for example, can have different temperature susceptibilities. As a result, it is possible that a softer (lower stiffness)

asphalt at temperatures above 25°C may become harder at low temperatures than the asphalt which was relatively harder (higher stiffness) at or above 25°C [18].

From the foregoing discussion, it is clear that the stiffness value at any given temperature is not sufficient to adequately evaluate the behaviour of asphaltic concrete mixes at low temperatures. A stiffness-temperature gradient, particularly in the low temperature region is also required to determine the temperature susceptibility of a mix. Figures 9 and 10 provide the stiffness-temperature relationships of the plant and laboratory mixes from different contracts, and Figure 11 compares the average stiffness gradient (plant and laboratory) of the recycled mixes from various contracts in the low temperature region (below 0°C).

Based on the results shown in Figures 9-11, the mixes can be ranked in order of their resistance to thermal cracking as follows:

Mix Type	Ranking	Remarks
HL4	1	Very high resistance
81-224, 81-74	2	High resistance
82-19	3	Medium resistance
82-04, 83-43**	4	Low resistance (**Based on plant mix test results only)

It can be surmised that the standard HL-4 mix has the highest resistance to thermal cracking in comparison to recycled hot mixes. Among recycled hot mixes, there exists some differences in the test results between the plant and

laboratory mixes for reasons as explained previously. However, the overall rating of the recycled mixes based on stiffness gradient indicates that the mixes from contracts 81-74 and 81-224 have relatively better resistance to thermal cracking as opposed to the mix from contract 82-04 which has the lowest resistance. The mix from contract 82-19 has moderate resistance to cracking at low temperature. Finally, based on plant mix test results, the mix from contract 83-43 also indicates very low resistance. The following section will review the above findings using the fracture temperature criterion.

6.2 FRACTURE TEMPERATURE CRITERION

Fracture temperature of a pavement is defined as the temperature at which the pavement cracks due to shrinkage. It could be estimated by plotting the failure strains determined from direct tension tests (section 5.2) and the induced thermal strains (section 5.3) of different pavement mixes against decreasing temperature as shown in Figures 12 and 13. Temperature at which the induced thermal strain exceeds the failure strain corresponds to the fracture temperature of the mix.

Table 9 provides the estimated fracture temperatures for all the mixes and their values are compared in Figure 14. The following observations can be made from Figures 12-14.

1) Laboratory mixes in general have higher fracture temperatures (i.e. lower resistance to thermal cracking) than plant mixes by 2-6°C. This is in agreement with the findings based on stiffness criterion (Figures 1-5) which indicate that laboratory mixes have higher stiffness values (lower

resistance) than plant mixes at temperatures equal to or less than the fracture temperatures of the corresponding mixes under investigation.

2) Mixes (plant and laboratory) from Contract 82-19 and plant mix from Contract 81-224 together with the standard HL-4 mix have fracture temperatures lower than -20°C, whereas mixes (plant and laboratory) from Contract 82-04 and 81-74 along with the laboratory mix from Contract 81-224 have fracture temperatures between -20°C and -13°C. The highest fracture temperature (-7°C) corresponds to the plant mix from Contract 83-43.

3) Based on the average (plant and laboratory mixed specimens) fracture temperature criterion, the mixes can be rated in order of very high, high, medium, and low resistance to cracking as follows:

Mix Type	Ranking	Remarks
HL4 82-19	1	Very high resistance
81-224	2	High resistance
81-74	3	Medium resistance
82-04 83-43**	4	Low resistance (** Based on plant mix results)

Table 10 provides the comparison of the results based on both criteria; stiffness and fracture temperature. For the purpose of analyses, average values of plant and laboratory mixes were taken into consideration. The similarities and differences between the two approaches are discussed as follows:

As can be seen from Table 10 both criteria indicate that,

1) HL-4 mix has relatively very high resistance to thermal cracking.
2) Mix from Contract 81-224 has moderate resistance to thermal cracking.
3) Mixes from Contracts 82-04 and 83-43 have low resistance to thermal cracking.

Minor discrepancies exist between the results based on these two criteria in respect of the mixes from Contracts 82-19 and 81-74. The former has medium resistance and the latter has high resistance to thermal cracking according to stiffness criterion. However, fracture temperature criterion indicates that the former has very high resistance and the latter has moderate resistance.

Finally, when the findings of the results based on both criteria are compared with the observed field data, it appears that both stiffness and fracture temperature criteria are suitable for evaluating low temperature performance of asphaltic concrete mixes. For instance, both criteria indicate that recycled hot mixes from contracts 82-19, 81-224, and 81-74 are less susceptible to cracking than those from contracts 83-43 and 82-04. This finding is consistent with the field data observed after three years of service which indicates (Table 11) that contracts 82-19, 81-224 and 81-74 have total pavement crack lengths between 100-400m as compared to the lengths of about 3000m for contracts 83-43 and 82-04. However, there is an advantage of using fracture temperature criterion because it is easier to select the winter design temperature for a given pavement once the temperature at which the pavement cracks is known. Also, it appears from Tables 1 and 11 that recycled hot mixes having low recycling ratio (contracts 82-19, 81-224 and 81-74) with high penetration grade virgin asphalt (300/400 for contracts 81-224 and 81-74) seem to provide improved resistance to thermal cracking.

7 CONCLUSIONS, AND RECOMMENDATIONS

7.1 CONCLUSIONS

The conclusions drawn from the analyses of the experimental results are presented as follows:

1) The findings confirmed the general belief that recycled hot mixes are more susceptible to thermal cracking than conventional hot mixes (HL4).

2) Among the different recycled hot mixes there is strong indication that mixes from Contracts 82-19, 82-224, and 81-74 have better resistance to cracking than those from Contracts 83-43 and 82-04 because of their relative lower stiffness and fracture temperature values.

3) It appears from the field data and the laboratory test results that the recycled hot mixes having low recycling ratio (contracts 82-19, 81-224 and 81-74) and with higher penetration grade virgin asphalt cement seem to perform better than the mixes having high recycling ratio (contract 82-04) and/or with low penetration grade virgin asphalt (contract 83-43).

4) Both stiffness and fracture temperature criteria can be used for assessing the potential of mixes to resist low temperature cracking. However, fracture temperature criterion will be more useful to determine accurately the winter design temperatures for asphalt pavements.

7.2 RECOMMENDATIONS

The following recommendations are made to improve the accuracy of predicting fracture temperature:

1) carry out additional direct tension tests at -15°C and -25°C to obtain more test data in the low temperature region, and
2) determine experimentally the actual rate of contraction of the specimen for a specific rate of cooling representative of field conditions and use the same rate to extend the specimen in the direct tension test.

As well, the following recommendations are made for designing RHM to minimize low temperature cracking:

a) choose an appropriate soft virgin asphalt cement (e.g. 300/400) to produce desirable final mix penetrations.
b) use low recycling ratio, and
c) determine fracture temperature and ensure compliance with winter design temperature.

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Table 1: Mix Design Properties of Recycled Hot Mixes and HL4 Mix

CONTRACT NUMBER	RECYCLING RATIO	ASPHALT CEMENT, %			Stability N	Flow	VMA %	Ret., % 4.75mm	Air Voids %
		ADDED	TOTAL	PEN					
81-224	60/40	2.7	5.2	300/400	10,000 (16,887)	9.2 (11.4)	N/A (14.6)	40	2.8 (1.4)
82-19	30/70	4.5	5.3	150/200	10,000 (12,080)	13.5 (14.2)	12.5 (14.3)	45	1.6 (1.0)
82-60	60/40	3.2	5.6	B.P.500	10,000 (10,346)	8.8 (8.8)	15.0 (15.0)	40	3.0 (3.3)
81-74	50/50	2.3*	5.0	300/400	16,760 (14,469)	12.5 (12.1)	N/A (14.8)	45	2.8 (2.8)
82-04	70/30	1.7	5.3	150/200	16,280 (17,658)	13.8 (13.5)	15.6 (15.3)	36	3.0 (1.9)
83-07	50/50	2.6	5.1	B.P.500	7,800 (10,884)	9.0 (11.4)	14.0 (13.9)	39	3.0 (1.5)
83-43	25/75 (DFC)	3.8	5.3	85/100	23,000 (24,042)	18.1 (17.4)	11.8 (9.5)	45	2.7 (2.6)
HL4	-	-	5.3	85/100	13600	10.4	13.8	45	4.0

* 0.5% antistripping agent added

Plant check results are given in parentheses

Table 2: AADT for Different RHM Test Sections

CONTRACT	REGION	HWY	LOCATION	YEAR					
				81	82	83	84	85	86
81-224	NORTH WESTERN	11	30km East of HWY633	600	550	550	500	500	500
82-19	CENTRAL	649	10km N. of Bobcaygeon	1000	1000	1000	950	950	950
82-60	EASTERN	62	2km N. of combermere			1250	1350	1350	1450
81-74	EASTERN	60	35km East of Renfrew	1500	1500	1500	1350	1350	1450
82-04	SOUTH WESTERN	21	5km S. of Thamesville	1900	2100	2100	2100	2100	2100
83-07	SOUTH WESTERN	2	6km W. of Thamesville			4600	4300	3600	3600
83-43	CENTRAL	QEW	Niag. Falls	26,200	26,000	28,200	30,000	32,150	33,400

Table 3 Recovered Asphalt Binder Properties of RHM

Contract	RAP		RHM	
	Pen @25°C mm	K. Visc. @ 135°C mm^2/sec	Pen @25°C mm	K. Visc. @ 135°C mm^2/sec
81-74	35	1073	53	457
81-224	31	517	57	326
82-04	28	508	36	498
82-19	20	1456	63	401
83-43	22	1167	30*	708*

* Recovered one year after construction

Table 4 Aggregate Description for Various Mixes

Mix Identification	Description	
	CA	FA
81-74	Crushed gravel containing Palaeo-zoic carbonates and marble granite	Silica rich natural sand
81-224	Crushed igneous gravel with mainly granite and granite gneiss	Silica rich natural sand
82-04	Crushed carbonate gravel with < 10% granite and gneiss	Silica rich natural sand
82-19	Crushed limestone gravel	Carbonate & silicate natural sand
83-43	Steel slag (DOFASCO)	Steel slag (DOFASCO)
HL-4	95% carbonate rock, 5% granite	95% carbonate rock, 5% granite

Table 5 Aggregate Gradations for HL4 and RHM Mixes

Mix		% Retained											
		Sieve size, mm								Sieve size, µm			
		19	16	13.2	9.5	6.7	4.75	2.36	1.18	600	300	150	75
HL4	CA			23.2	68.5	89.0	98.1	98.3	98.5	98.7	98.8	99.0	99.2
	FA						1.0	20.1	39.0	58.6	82.4	92.4	96.7
	Final			10.5	31.0	40.3	45.0	55.5	65.9	76.7	89.8	95.4	97.8
81-74	RAP			3.2	13.4	26.0	36.8	50.7	60.9	71.5	84.1	91.0	94.8
	CA		4.3	20.4	63.7	88.3	92.7	93.6	94.5	95.4	96.2	97.1	98.0
	FA						0.4	1.4	5.3	21.0	60.6	88.8	95.9
	Final		1.3	7.5	25.1	38.4	45.0	52.2	58.3	67.2	82.4	92.3	96.0
81-224	RAP		1.3	5.8	24.0	38.9	49.0	62.4	72.9	81.2	87.6	91.7	94.9
	CA		2.8	17.2	55.7	81.6	94.6	95.2	95.7	96.3	96.9	97.4	98.0
	FA					1.0	9.1	29.4	51.3	72.2	87.8	95.1	97.9
	BLSA	0.5	1.0	1.6	3.6	5.7	8.3	17.1	32.2	55.8	85.3	97.5	99.4
	Final		1.0	4.9	19.6	31.2	40.0	52.6	94.9	77.0	88.1	93.7	96.4
82-04	RAP	2.0	4.0	7.0	18.0	33.0	44.2	57.0	64.0	71.0	84.0	93.0	95.5
	CA		0.3	8.5	59.9	88.7	98.1	98.3	98.6	98.8	98.0	89.3	99.5
	FA				0.5	1.0	2.0	4.1	8.0	14.5	33.9	81.7	94.2
	Final	1.4	2.8	5.3	15.6	27.5	36.0	45.4	51.2	57.8	71.8	90.4	95.4
82-19	RAP	1.3	6.7	10.0	23.0	34.7	45.0	59.7	70.3	79.0	87.0	93.0	96.0
	CA		3.5	19.5	63.4	88.5	97.6	97.9	98.2	98.5	98.8	99.1	99.0
	FA						1.9	16.4	35.1	51.5	70.2	83.1	91.1
	BLSA				1.4	2.9	5.3	12.3	24.1	39.8	65.6	88.5	96.1
	Final	0.4	3.1	9.0	26.8	38.3	45.0	53.7	62.9	71.9	83.1	92.1	96.2
83-43	RAP			1.0	8.0	22.0	32.0	46.0	58.0	68.0	80.0	89.0	92.8
	CA			2.0	34.6	69.7	94.5	95.2	95.9	96.7	97.4	98.1	98.8
	FA							39.1	62.4	75.4	85.0	91.1	95.2
	Final			1.0	15.6	32.8	45.0	62.9	74.6	92.2	88.7	93.4	96.0

Table 6 Experimental design for direct tension tests

Mix type		Temperature°C		
		21	-5	-35
81-74	Plant	2	2	2
	Lab	2	2	2
81-224	Plant	2	2	2
	Lab	2	2	2
82-04	Plant	2	2	2
	Lab	2	2	2
82-19	Plant	2	2	2
	Lab	2	2	2
83-43	Plant	2	2	2
	Lab	-	-	-
HL4	Lab	2	2	2

Note:- Two samples per cell

Table 7 Thermally Induced Strains (x10^-3 mm/mm) for Plant Mixes

Temperature °C	Mix Type					
	Control	81-74	81-224	82-04	82-19	83-43
-38	1.22	0.986	0.7	0.91	0.71	1.0
-29	1.12	0.796	0.7	0.815	0.71	0.8
-7	0.51	0.696	0.335	0.509	0.339	0.635
4	0.20	0.497	0.335	0.3	0.271	0.440

Table 8 Thermally Induced Strains (x10^-3 mm/mm) for Laboratory Mixes.

Temperature(°C)	81-74	81-224	82-04	82-19
-38	1.479	1.49	0.689	0.996
-8	-	-	0.49	0.49
-5	.39	.49	-	-

Table 9 Failure strains ($x10^{-3}$ mm/mm) and fracture temperature of various mixes

Mix	Test Temperature °C			Fracture Temperature °C
	21	-5	-35	
HL4	7.545	2.630	0.096	-23
81-74P	3.635	1.555	0.152	-19
81-74L	2.975	1.056	0.095	-13
81-224P	4.310	1.979	0.103	-22.5
81-224L	3.820	1.574	0.160	-17
82-04P	2.315	0.842	0.090	-13
82-04L	1.440	0.698	0.148	-13
82-19P	5.695	2.615	0.079	-26
82-19L	4.958	2.050	0.107	-24
83-43P	1.465	0.603	0.212	-7

Table 10 Resistance of various mixes to thermal cracking

Mix Type	Stiffness Criterion	Fracture Temperature Criterion
HL4	Very High	Very High
81-224	High	High
81-74	High	Medium
82-04 83-43*	Low	Low
82-19	Medium	Very High

* Based on plant mix test results only

Table 11 Condition Survey Data

Contract	Cracks, m/km lane (Three years after construction)					
	Type A	Type B	Type C	Type D	Type T	Total
82-19	65	54	0	0	0	119
81-224	30	168	127	0	0	325
81-74	53	249	97	18	0	417
82-04	198	2068	492	151	0	2909
83-43*	34	31	5	0	2896	2966

Note:

A = Hairline crack
B < 5mm
C =5-10mm
D =10-20mm
T = Treated
* = Two years after contruction

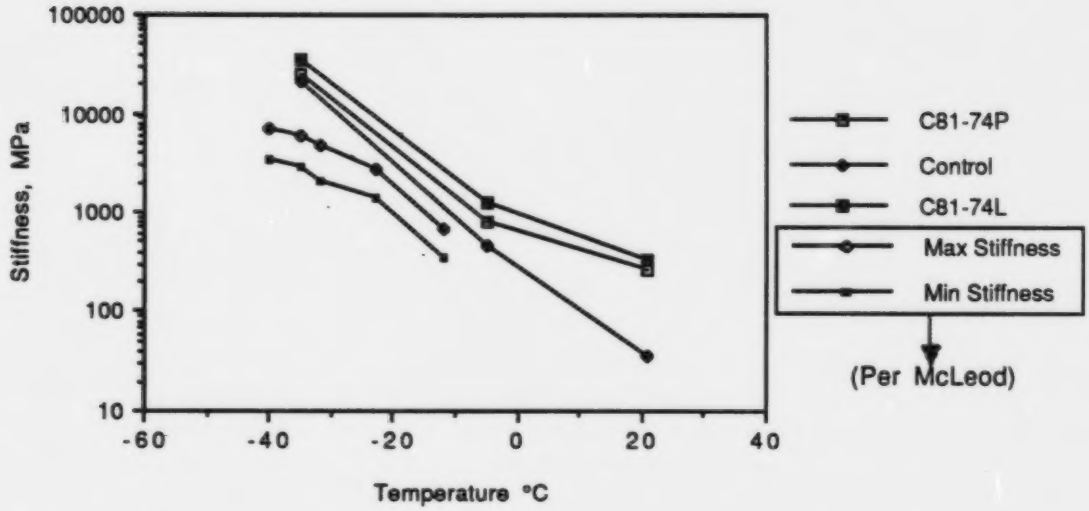


Figure 1 Stiffness-temperature relationship (cont. 81-74)

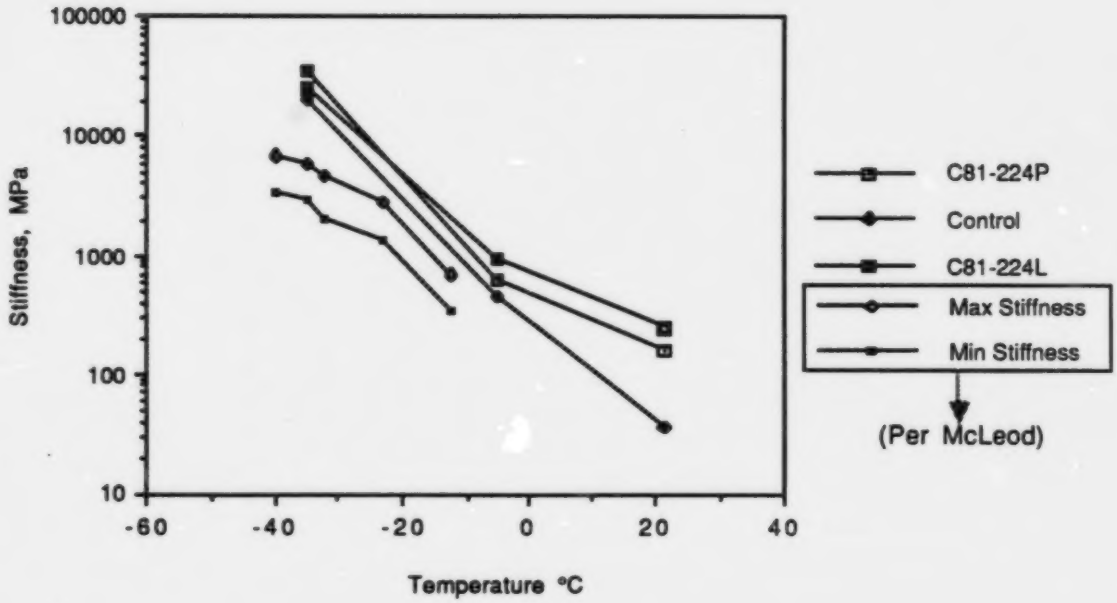


Figure 2 Stiffness-temperature relationship (cont. 81-224)

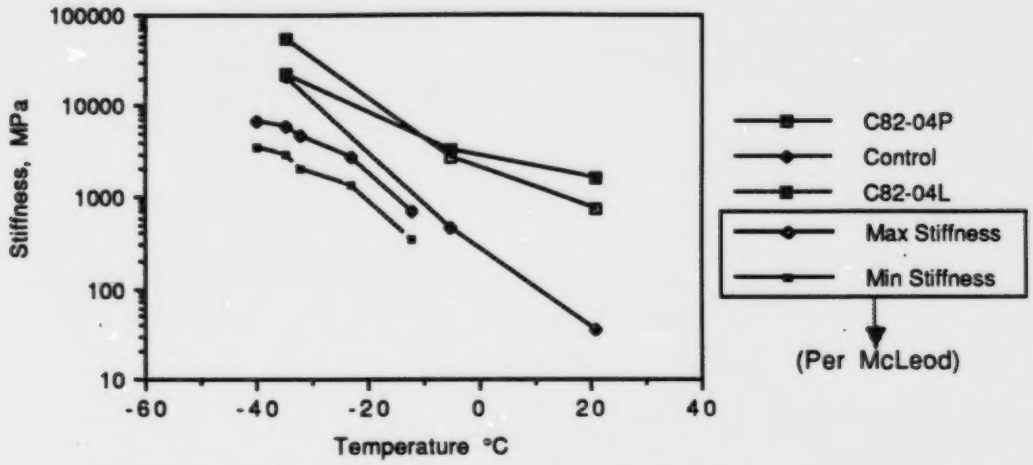


Figure 3 Stiffness-temperature relationship (cont.82-04)

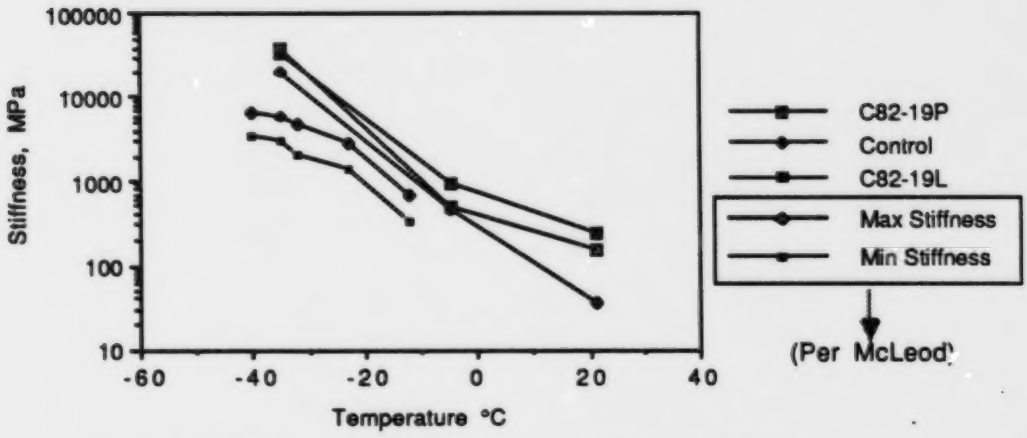


Figure 4 Stiffness-temperature relationship (cont.82-19)

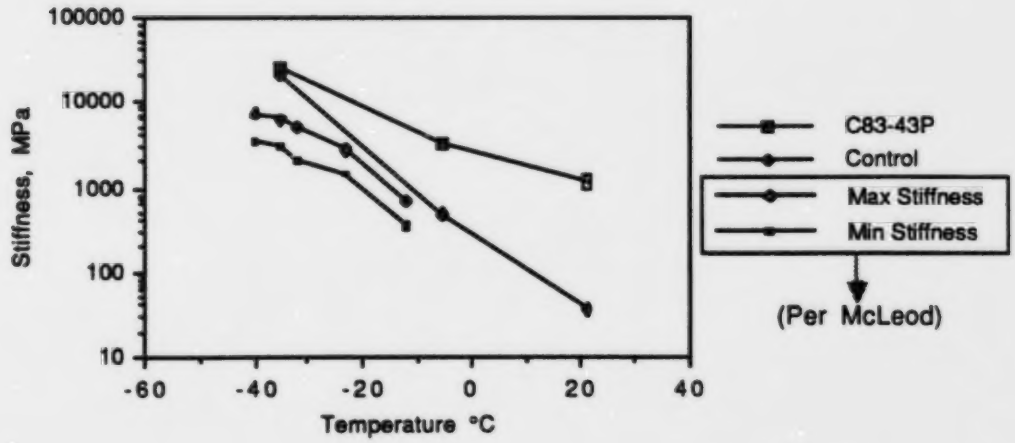


Figure 5 Stiffness-temperature relationship (cont.83-43)

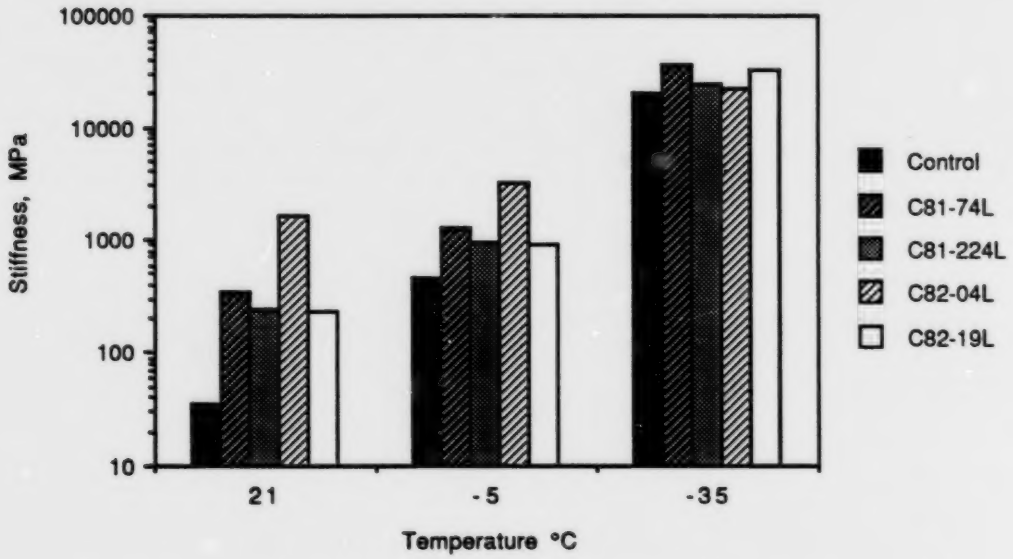


Figure 6 Comparison of laboratory mix stiffnesses at different temperatures

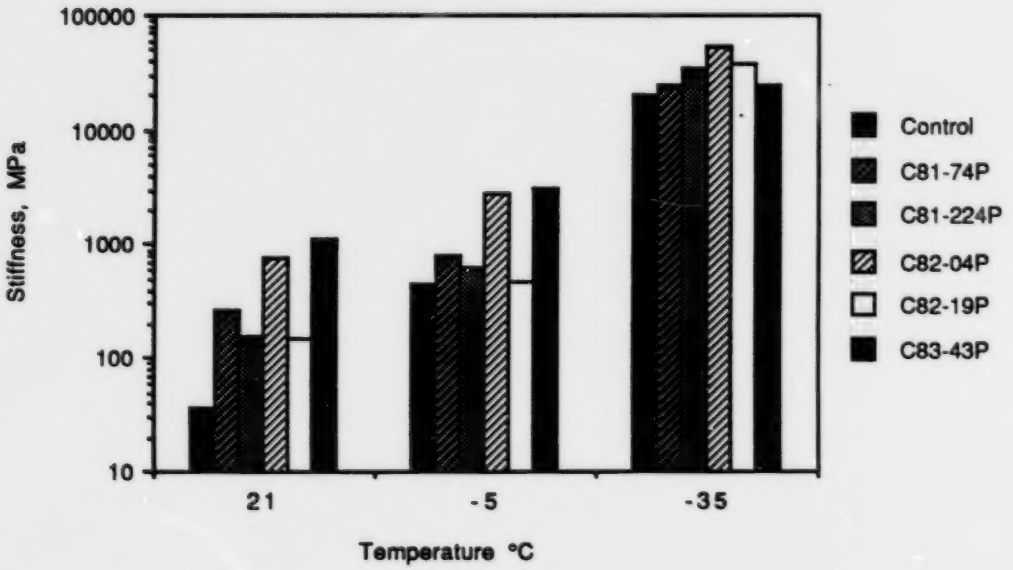


Figure 7 Comparison of plant mixes at different temperatures

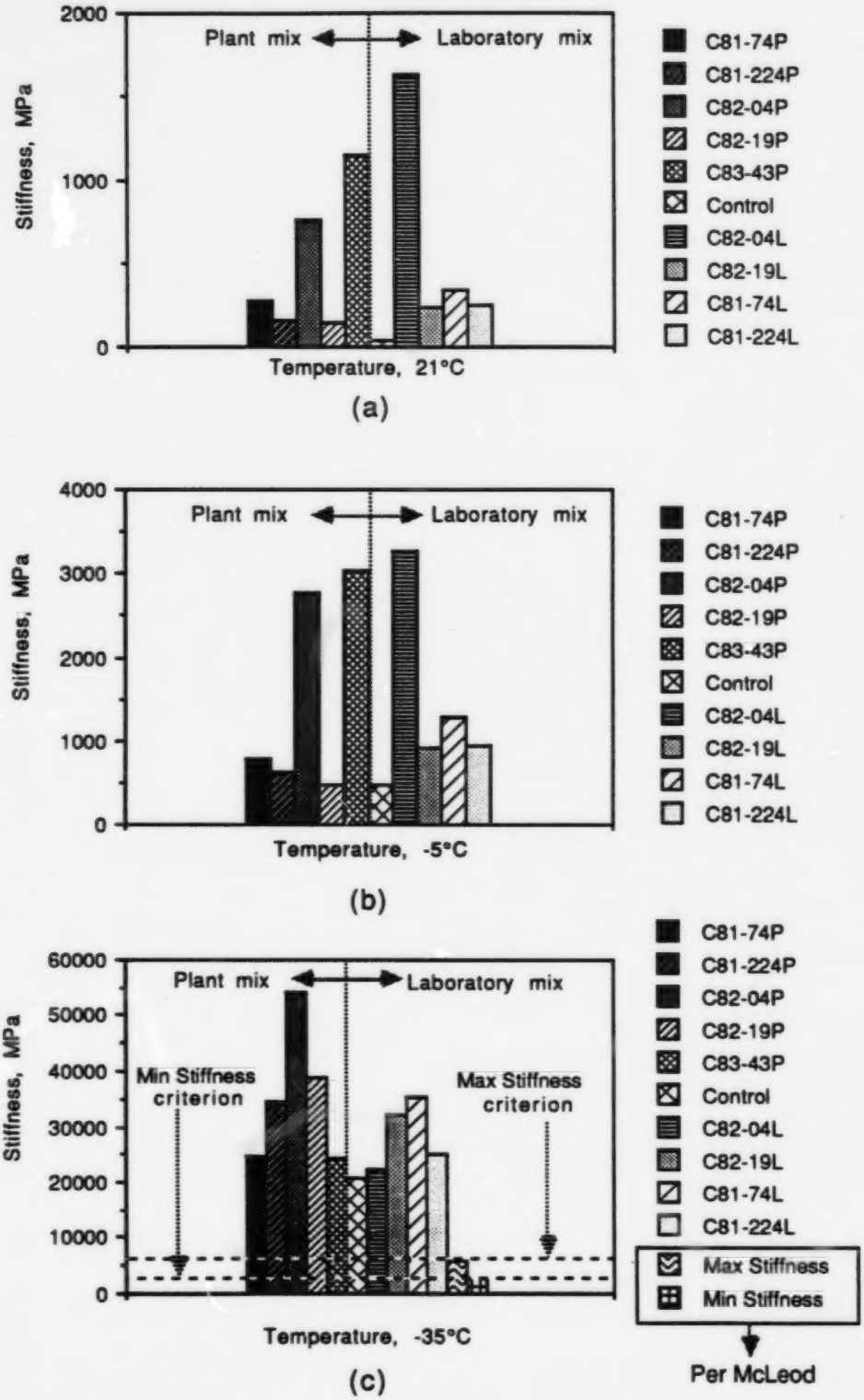


Figure 8 Comparison of Plant and Laboratory mix stiffnesses at various temperatures

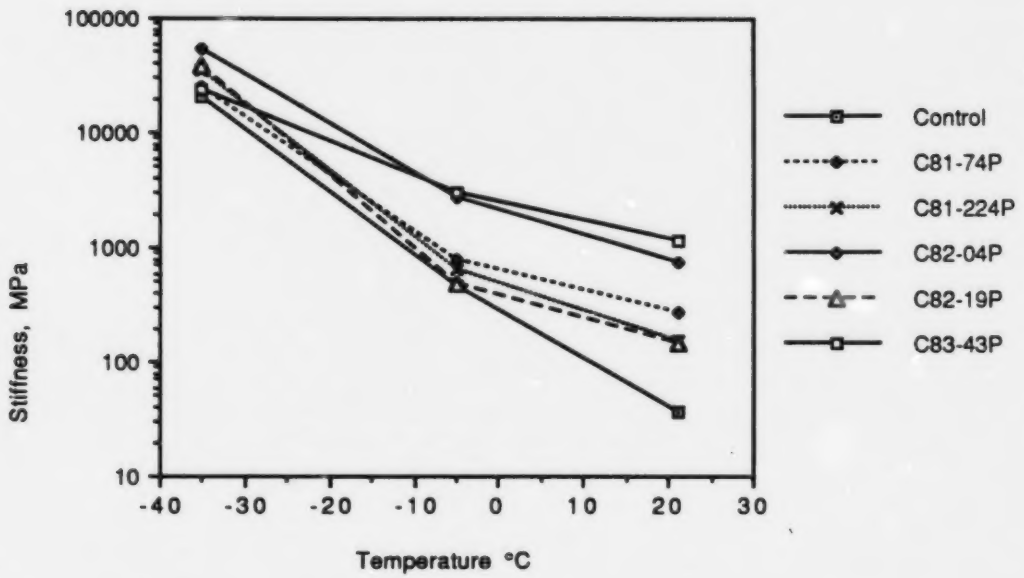
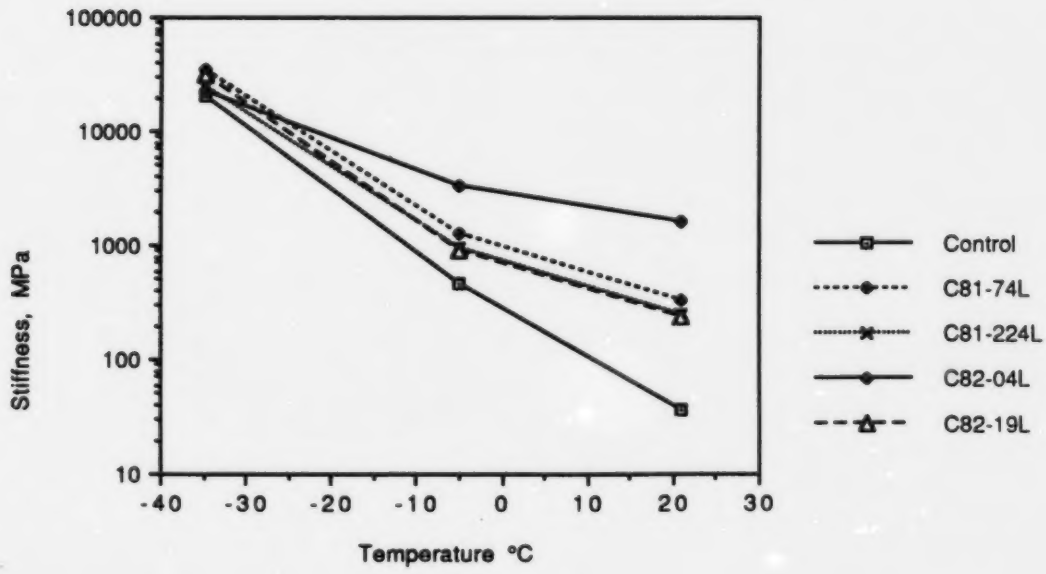


Figure 9 Stiffness gradients for plant mixes



Figur 10 Stiffness gradient for laboratory mixes

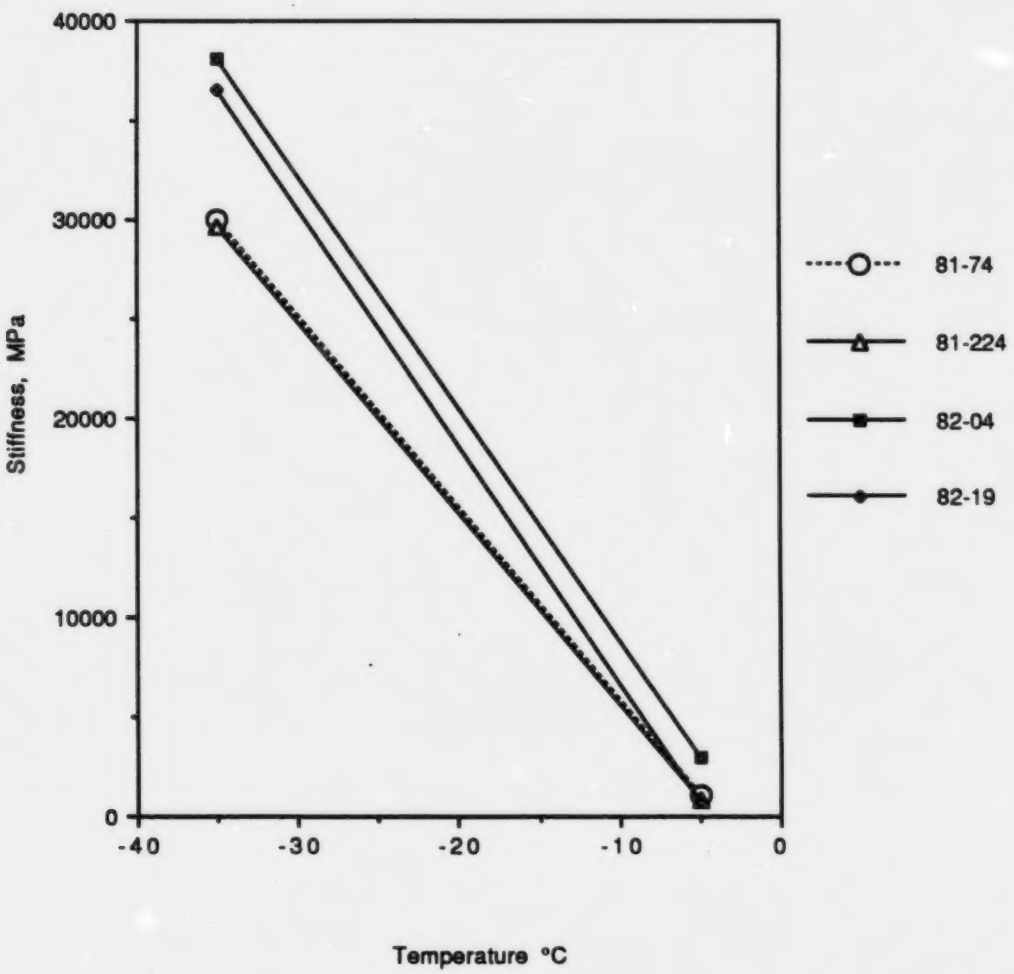


Figure 11 Average stiffness gradient for recycled mixes (below 0°C)

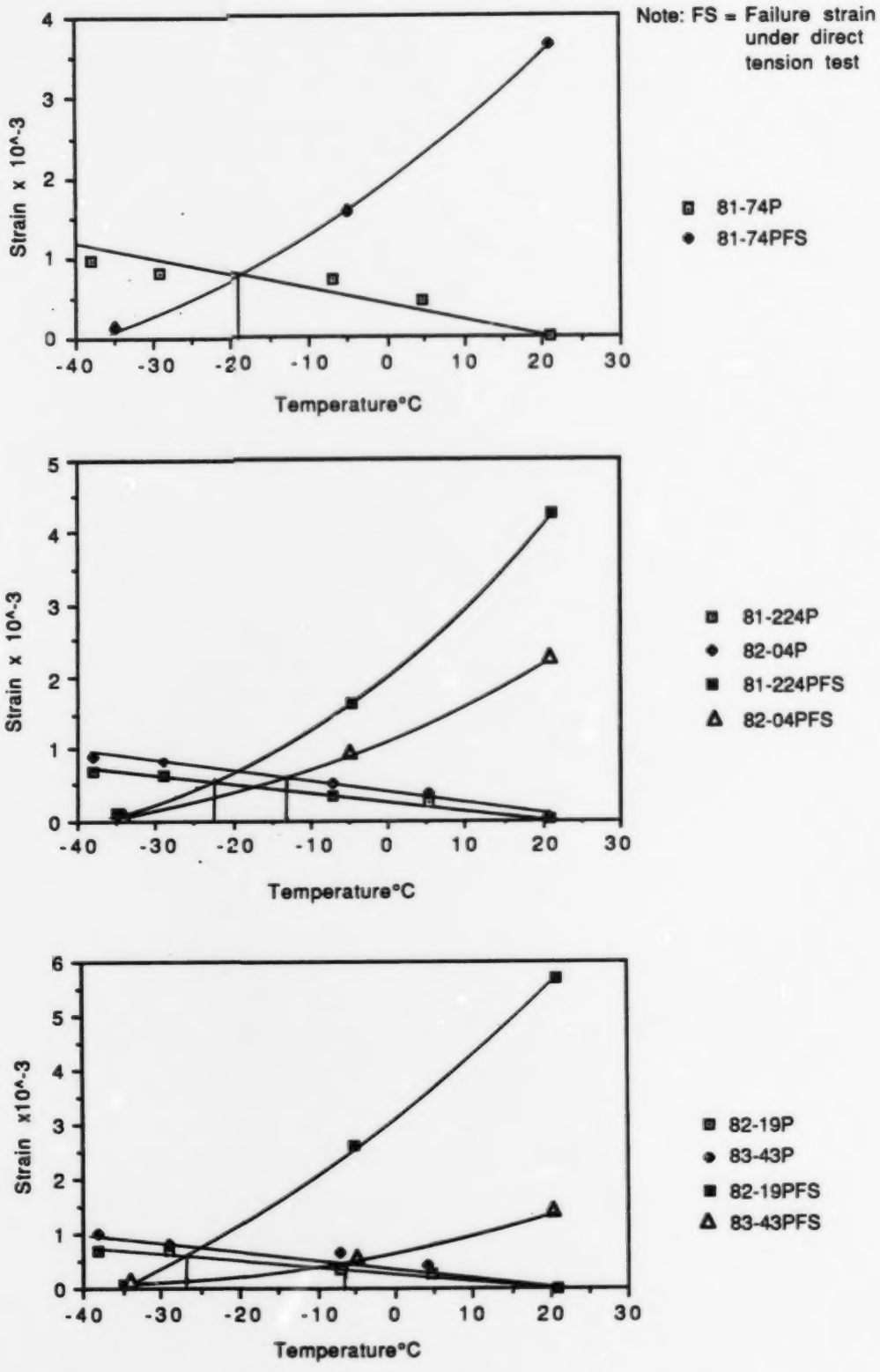


Figure 12 Estimation of fracture temperature for plant mixes.

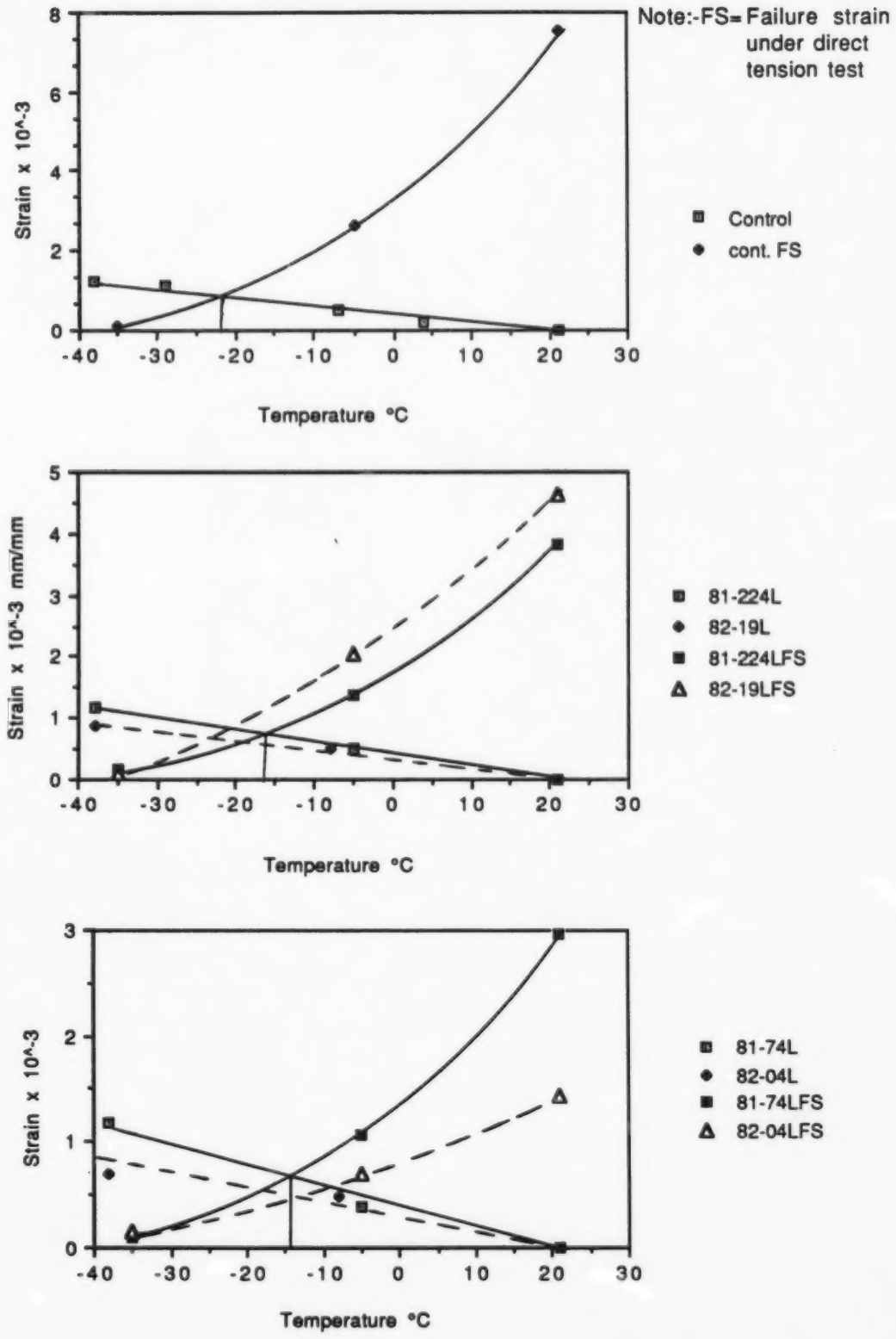


Figure 13 Estimation of fracture temperature for laboratory mixes

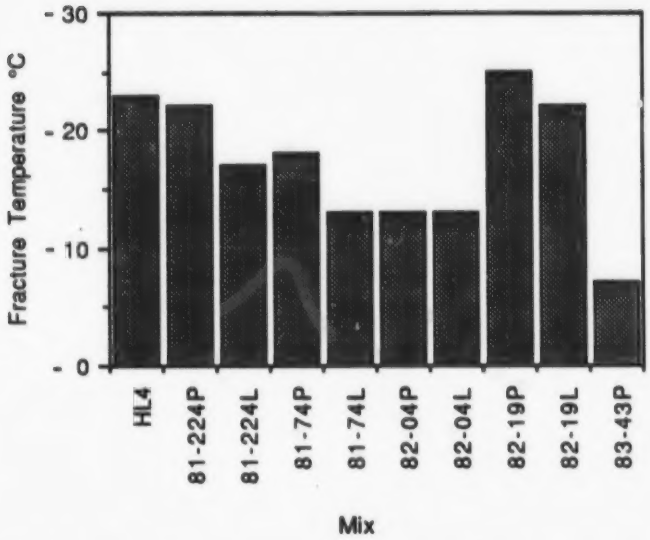


Figure 14 Fracture temperature comparison of various asphalt mixes